Sediment Transport

- Dissolved load
  - Travels in solution
- Suspended load
  - Particles transported in water column, not in contact with bed
- Bed load
  - Particles transported by rolling, sliding, or saltation

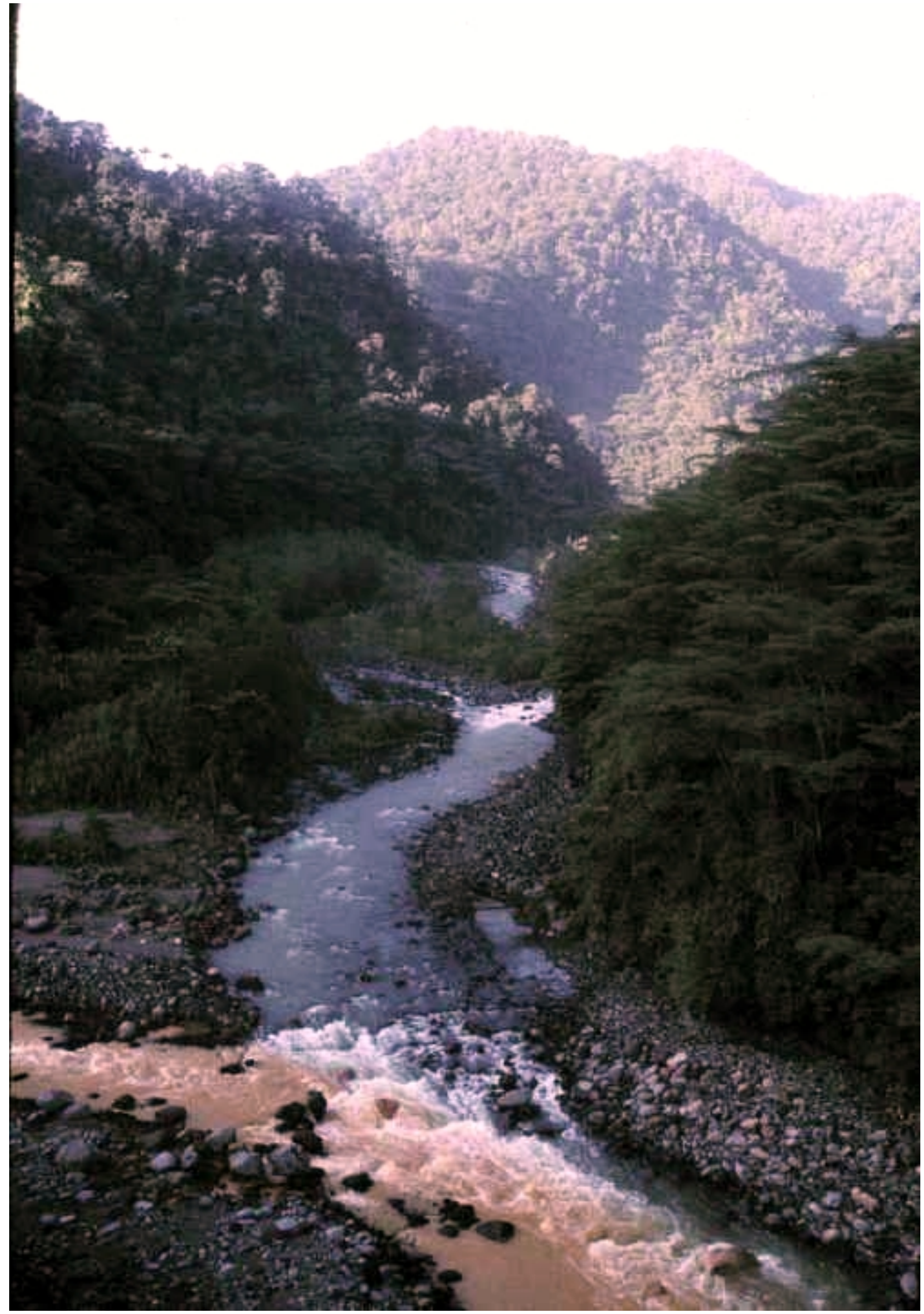


Photo by Dawn Summer, UC Davis

Sediment transport

- In terms of denudation rates: dissolved and wash load are most important
  - Dissolved load ~20% of total
  - Suspended load ~70% of total
- In terms of geomorphic work: bed material load is key

Transport mode versus size

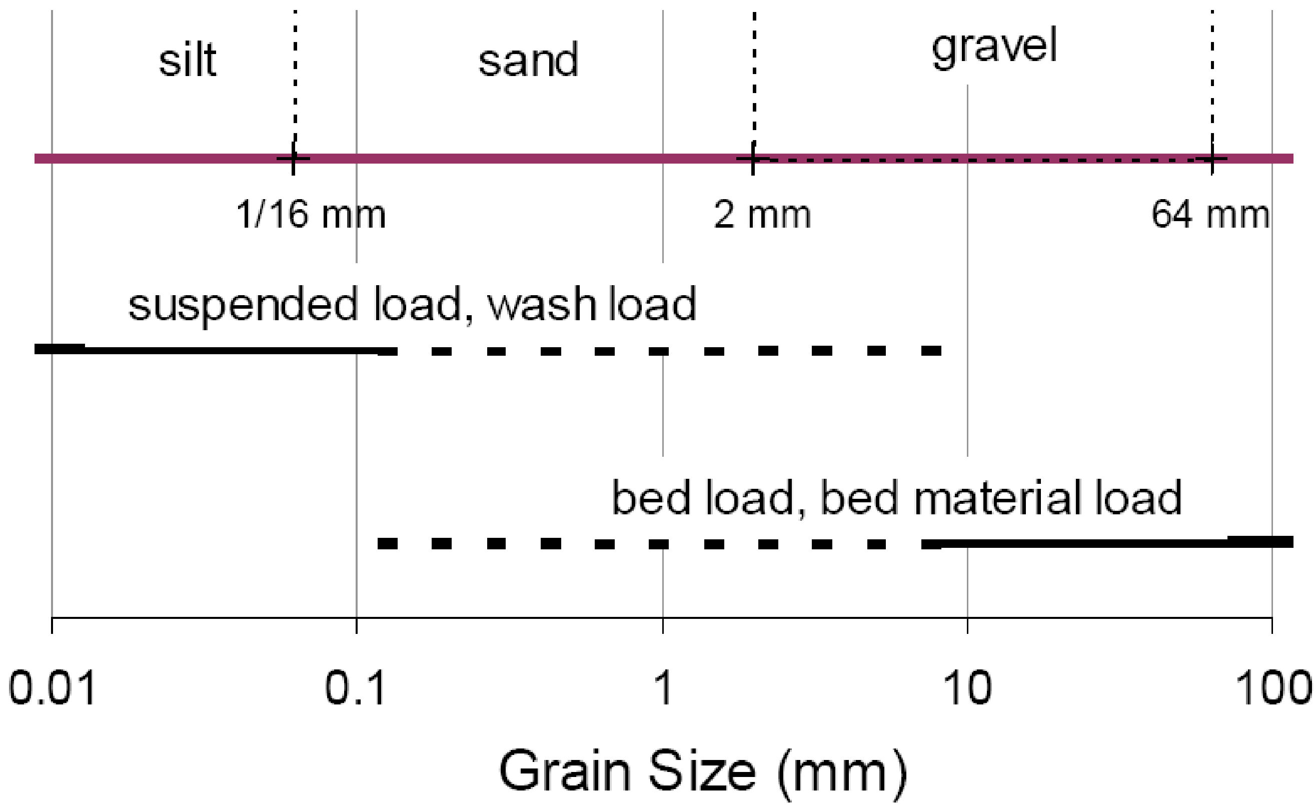


Figure from Peter Wilcock

Magnitude vs. Frequency Effects

Most of the time	Sometimes *2 to 6 weeks per year*	Only briefly *0-3 weeks per year*	v. Rarely *Every decade or two*
Not much happens	Moderately high flows; some transport of fines (sand) over immobile coarse bed	High flows, moving larger grains making up bed framework	Monster floods
	Sand may collect into pools, infiltrate into interstices	Bed scour & aggradation, bar building & migration, bank erosion & other geomorphic action	Reset the channel bed and, often, its geometry

Figure from Peter Wilcock

Dissolved load ------------------------------------

Suspended load ---------------------

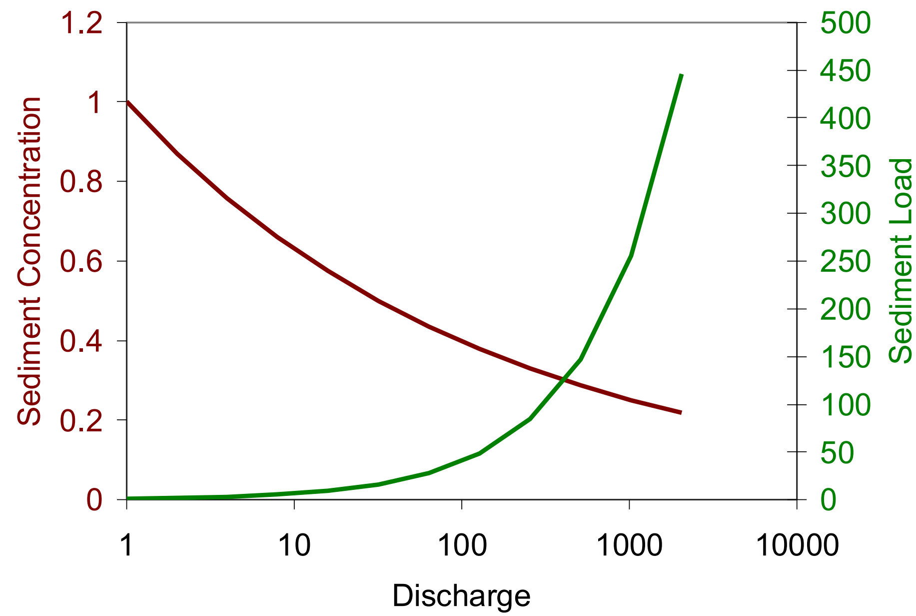
Bed load ----------------------

Dissolved load

- Solute concentration (C) declines with discharge (Q) → dilution effect

$$C = aQ^b$$

b<0 (often ~-0.2)



- Solute load (Q_{diss}) increases with discharge

$$Q_{diss} = C \times Q$$

Recommended reading: Godsey, S. E., Kirchner, J. W., & Clow, D. W. (2009). Concentration–discharge relationships reflect chemostatic characteristics of US catchments. *Hydrological Processes*, *23*(13), 1844-1864.

- High dissolved load
- River Wye, England flows through limestone

- High suspended load
- Huang He River, Lanzhou ("Yellow River") drains Loess Plateau

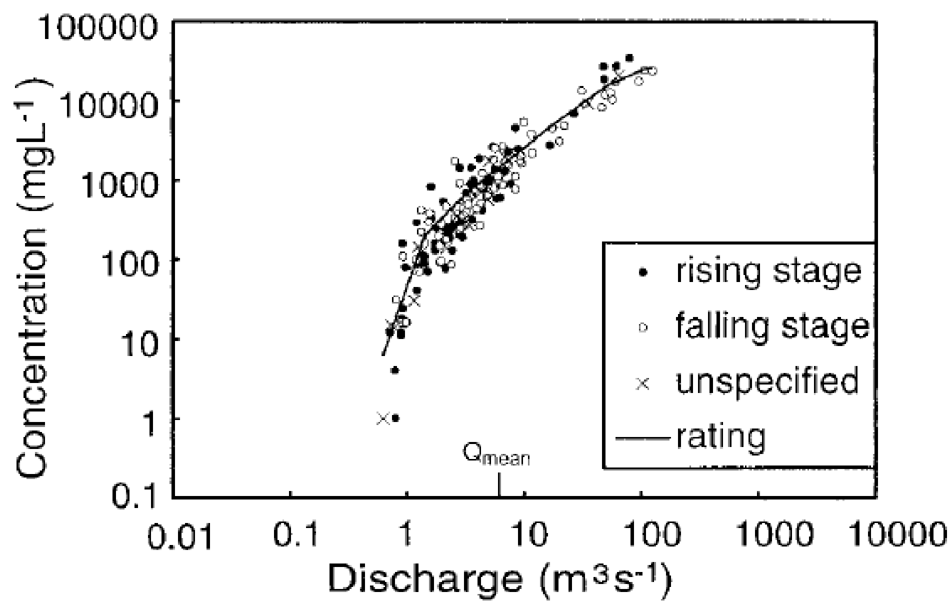
Suspended sediment

Suspended sediment is generally supply limited:

- Supply limited: Sediment load is controlled by the rate it is delivered to the river
- Transport limited: Sediment load is controlled by the transport capacity of the river

Even so,

$$C = aQ^b,$$
$$b \sim 1\text{-}2$$



Hicks et al. 2000 WRR

Hysteresis

- Dissolved and suspended concentrations v. Q are dependent on history
- Concentrations higher on the rising limb of an event and earlier in the season → supply effect
- Concentrations higher on falling limb → wave vs. water velocity

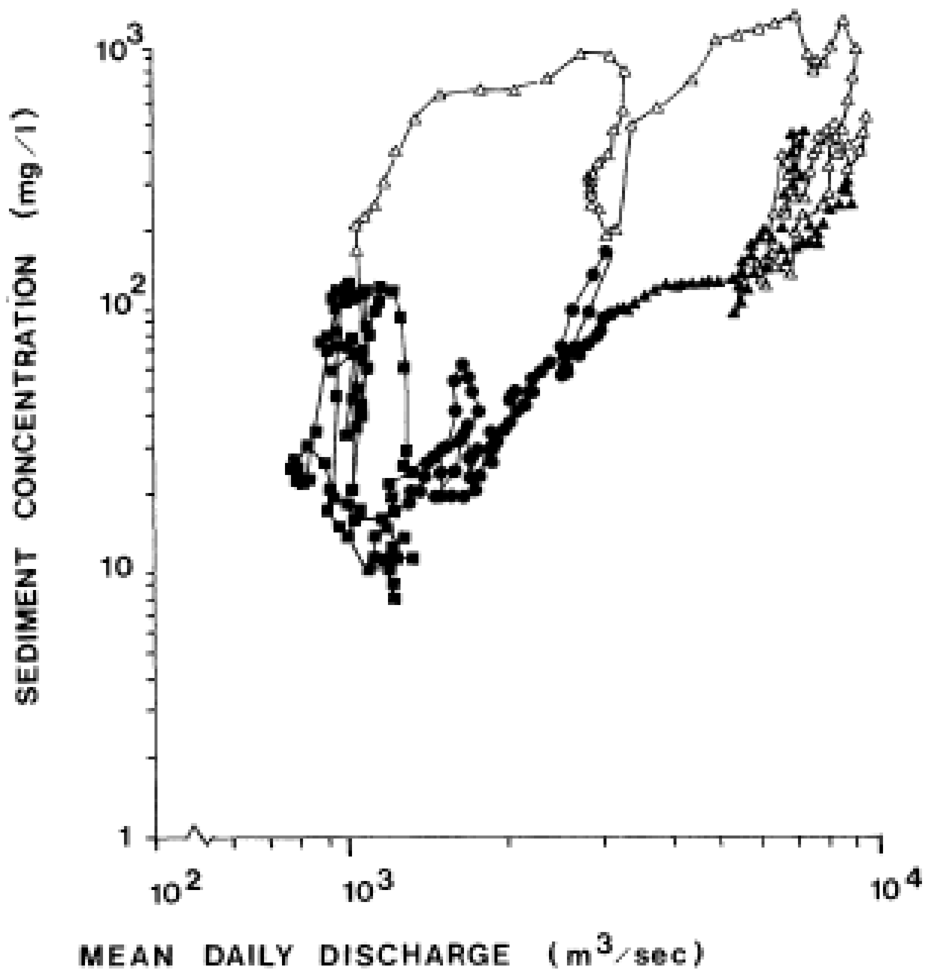


Fig. 1. Hysteresis in discharge–sediment concentration relationships in the Fraser River at Hope, British Columbia, as shown by daily observations (■—January–March; △—April–June; ▲—July–September; ●—October–December).

Whitfield and Schreier 1981 Limnol. Ocean.

- Very high concentrations of susp. sed.(>20%)
  - Reduce turbulence
  - Increase viscosity
  - Reduce settling velocities
  - → transport larger sediment

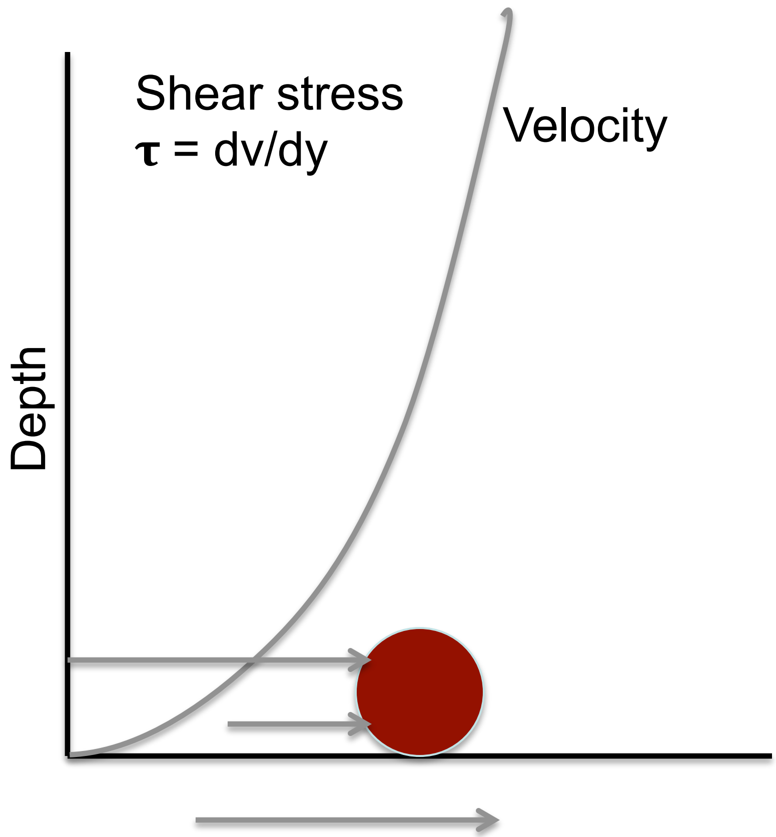
Toutle River, Washington

What does bed load transport look like?

- http://all-geo.org/jefferson/bedload-transport-videos-ftw/

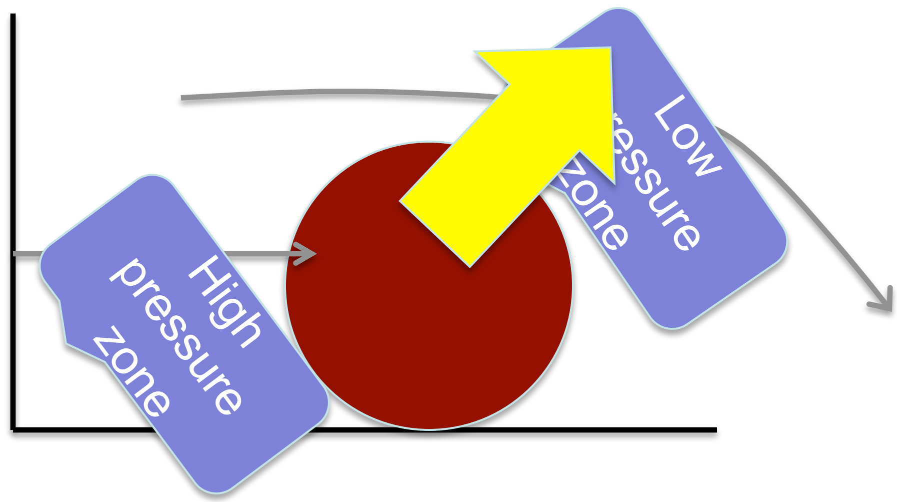
How do grains begin to move?

Drag Force



Differential velocity between top and bottom of grain → shear stress → rolling, sliding

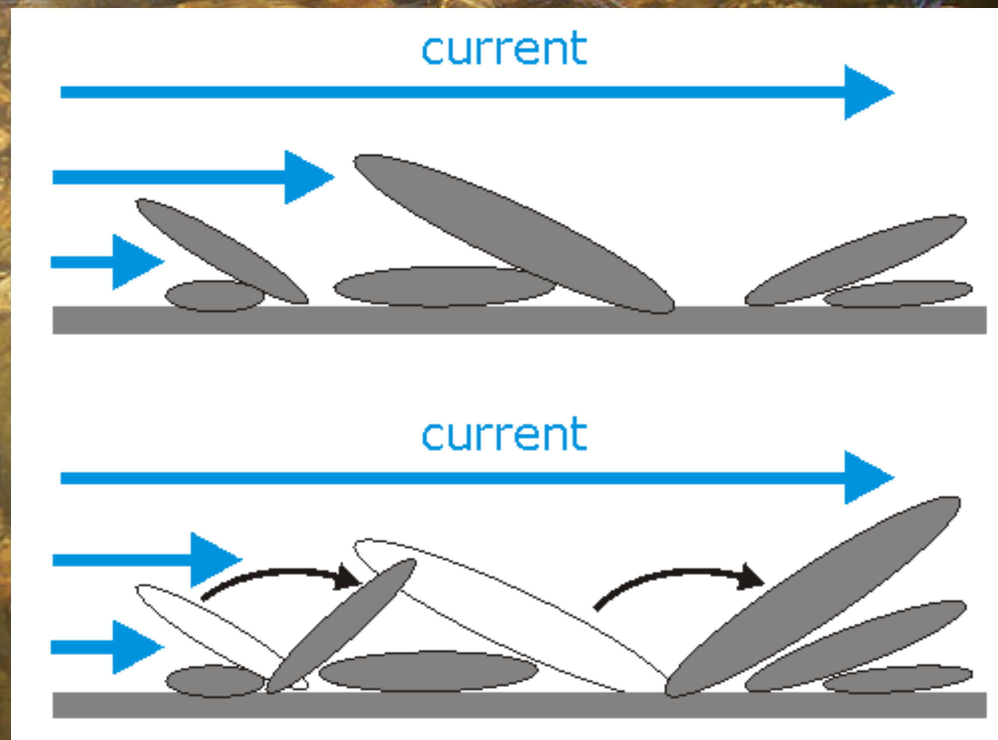
Lift Force



Boundary layer + turbulence creates pressure differences → Pressure difference "pulls" grains off the bed (Bernoulli Principle) → saltation

Which grains move?

- Size
- Density
- Settling velocity
- “Hiding”

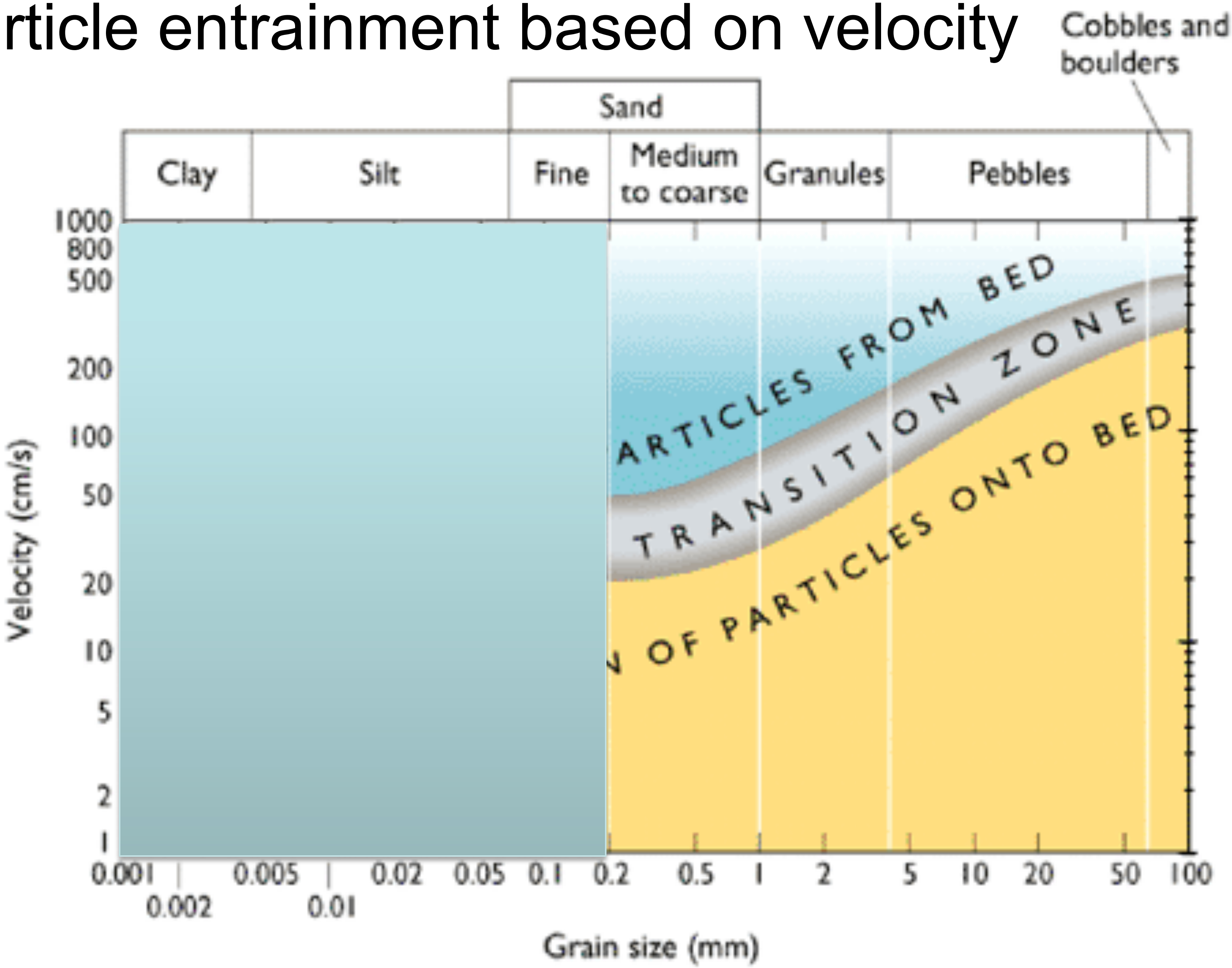


Variables relevant to bed load transport

- **Flow properties:** discharge, velocity, depth, width, slope, roughness
- **Fluid properties:** viscosity, density, temperature, suspended load concentration
- **Sediment properties:** density, size distribution, fall velocity
- **Other:** gravity, planform geometry

Hjulström diagram

particle entrainment based on velocity



Bed Load Transport

- Bed load transport is a function of shear stress on the channel bed (i.e., boundary shear stress)

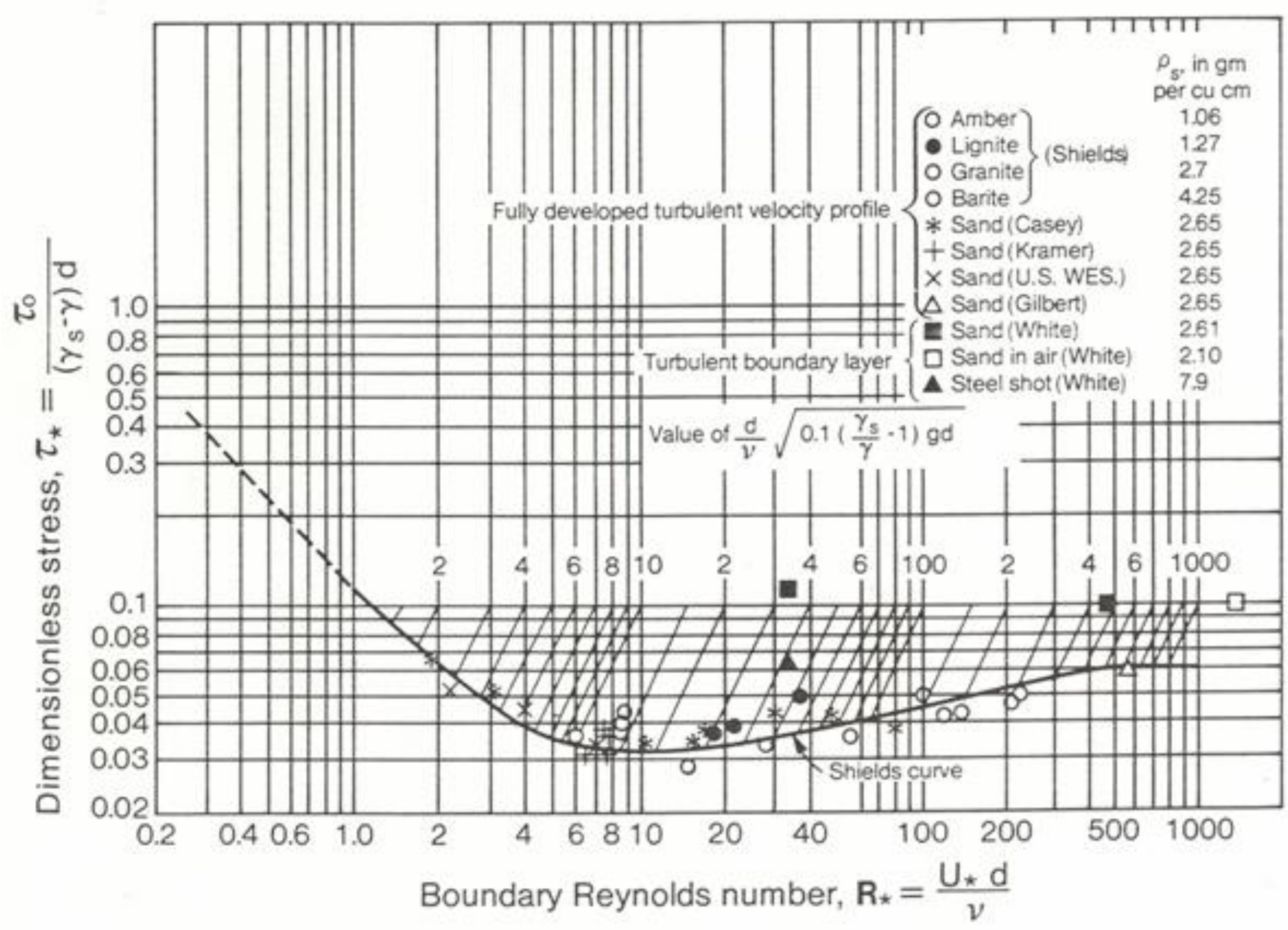
$$\tau = \rho g R S$$

- Transport begins when conditions exceed a critical boundary shear stress. τ_c
- Bed load transport is a function of:

$$q_b = k(\tau - \tau_{cr})^n$$

Shields' diagram tells us about initiation of motion

- …this is critical



Incipient motion

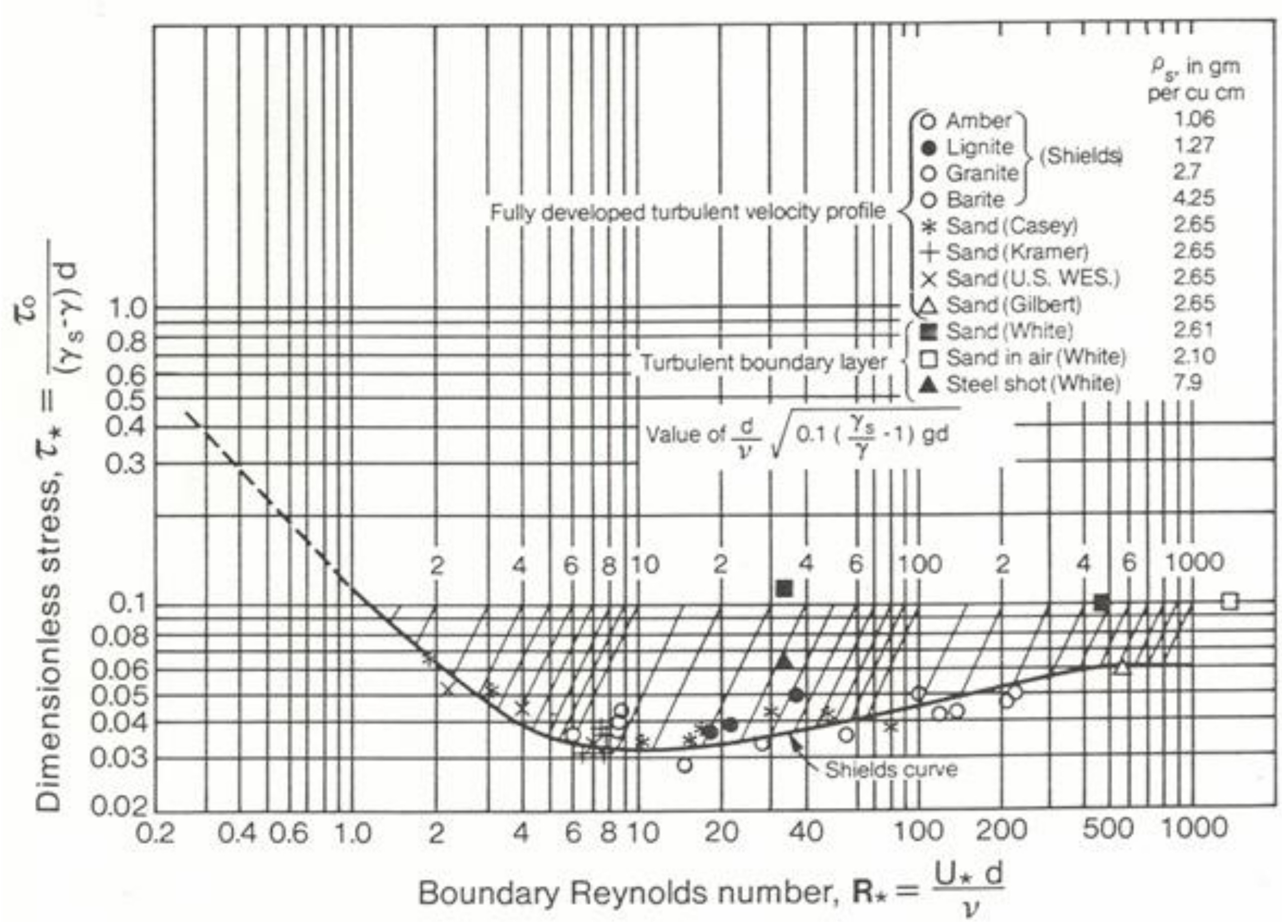
For D > ~0.5 mm: $\tau_{cr^*} \sim 0.045 \rightarrow$

$$\tau_{cr} = 0.045g(\rho_s - \rho_w)D$$

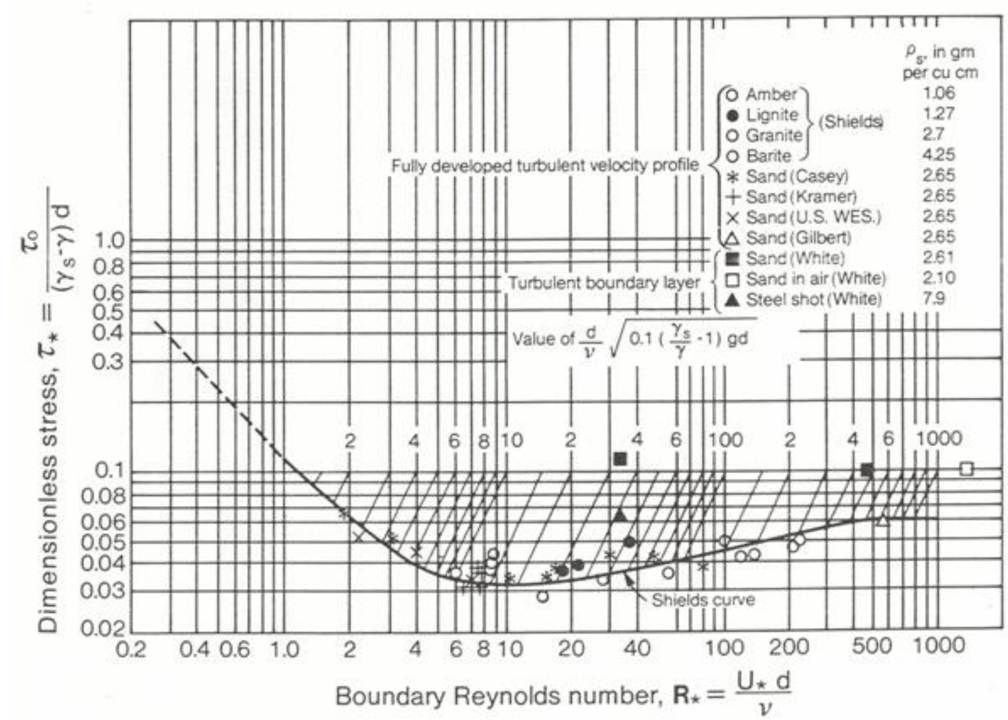
Grain diameter

If D = 1 mm, ps = 2.65 g/cm^3, is τ_c exceeded in a very wide channel with flow 1 m deep and slope of 0.001.

What is threshold size for transport?



Incipient motion



- For D < ~0.5 mm, use equation, then dimensionalize

$$\boxed{\mathrm{Re}_{cr*}} = \frac{D}{\upsilon}\sqrt{0.1\left(\frac{\gamma_s}{\gamma}-1\right)gD}$$

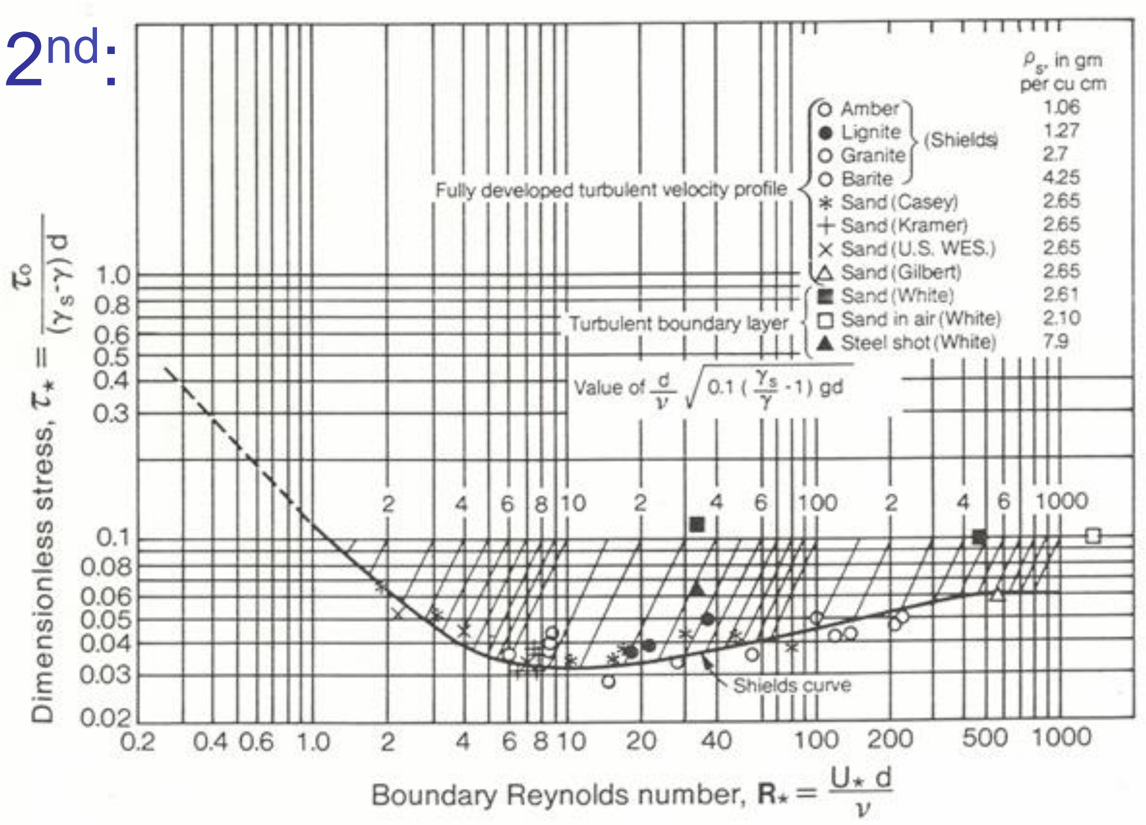
Example Problem

- River flow occurs as follows: $Q = 100\ m^3/s$, average depth = 1 m, average velocity = 0.50 m/s, channel slope = 0.0001, water temperature = 5°C, viscosity (ν) = 1.51×10^{-6}, median size of 0.4 mm and a density of 2.65 g/cm^3.
- What is the critical shear stress for incipient motion?

Example Problem

1st: $$\mathrm{Re}_{cr*} = \frac{D}{\upsilon}\sqrt{0.1\left(\frac{\gamma_s}{\gamma}-1\right)gD}$$

2nd:



3rd:

$$\tau_{cr} = \tau_{cr*}g(\rho_s - \rho_w)D$$

Bed Load Transport

- Simplified bed load transport equations take the form:

$$q_b = k(\tau - \tau_{cr})^n$$

- Real transport models are ugly:

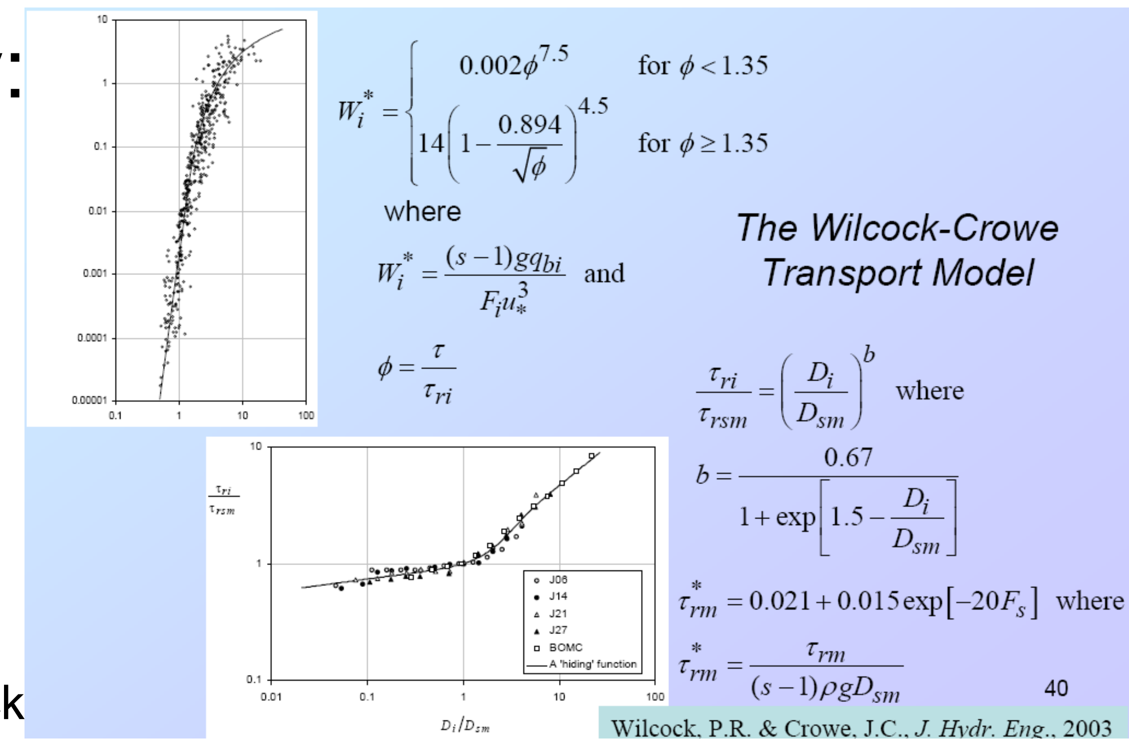


Figure from Peter Wilcock

Models versus Measurements

Model PROs

- Allow predictions in streams without data
- Allow us to test our understanding of the physics
- They are dry and safe
- They are cheap and instantaneous
- Measurements aren't perfect

Measurement PROs

- Measurements provide real data for a particular site
- Measurements can be used to create a rating curve
- Models have big uncertainties
- Models need some field data to begin with

Measuring Bed Load

Helley-Smith sampler

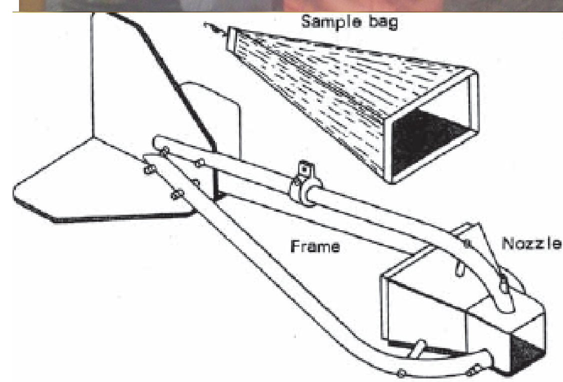


Figure 7.27 Helley–Smith bed-load sampler (Emmett, 1979).

Net frame samplers

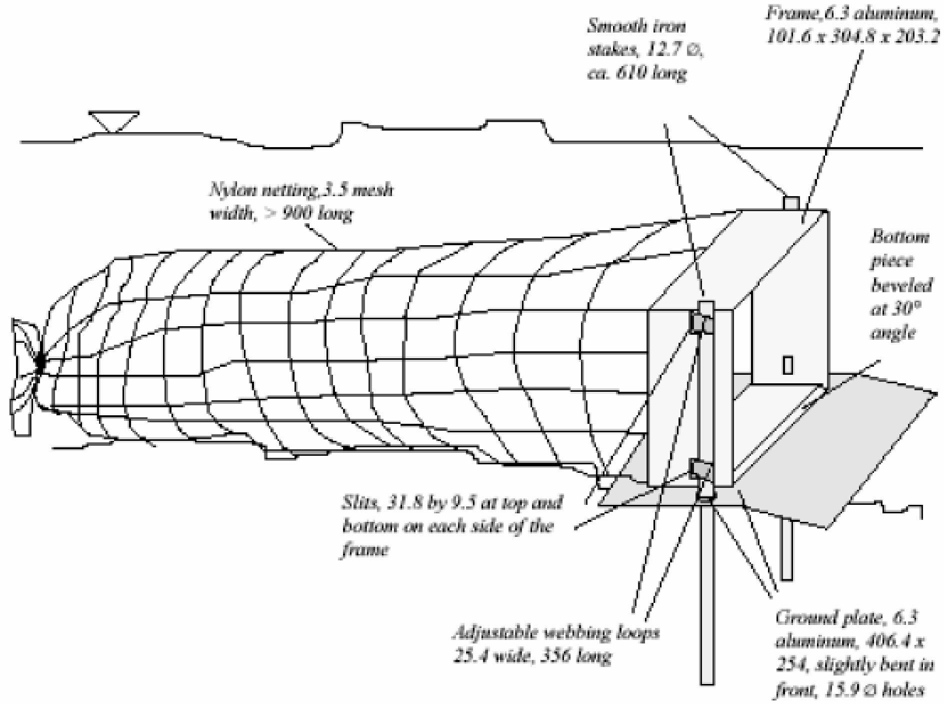
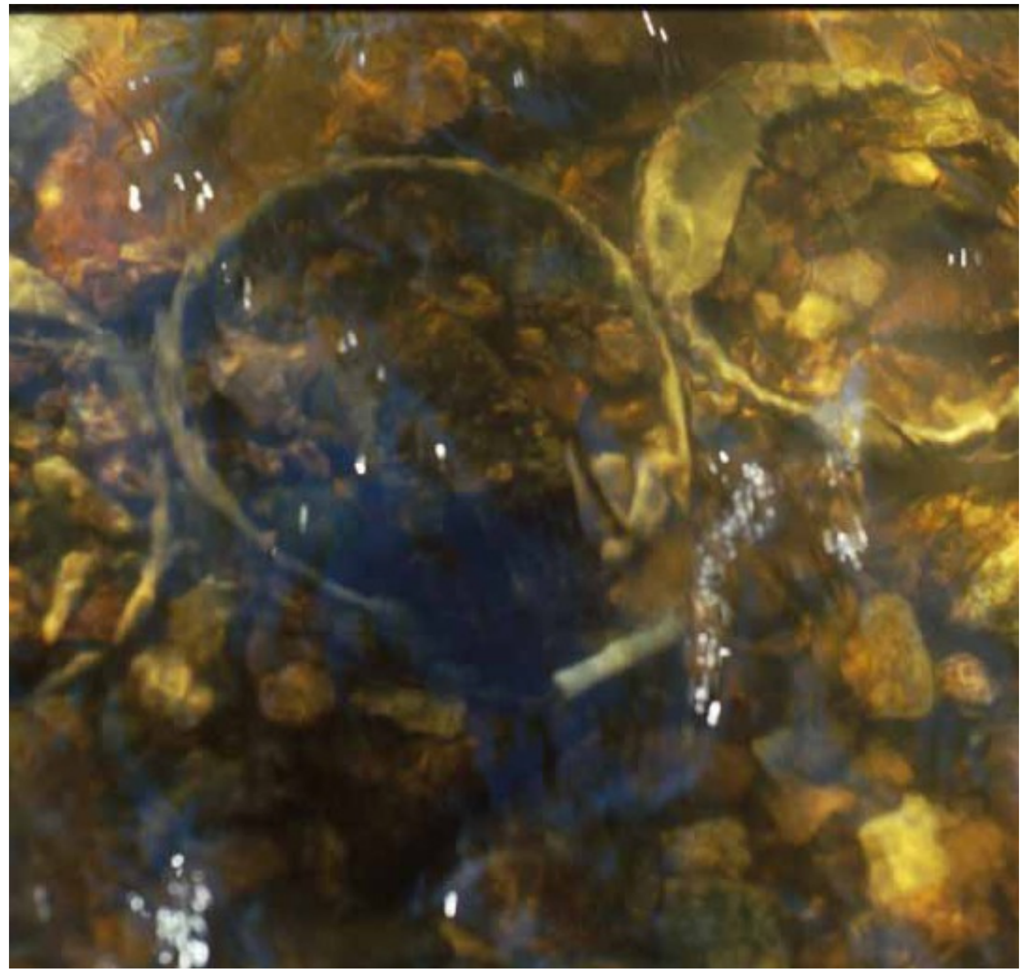


Fig. 1: Schematic diagram of a bedload trap. All measurements in mm (from Bunte 1998).

Only work at low flow rates

Sediment Traps



Tracer Gravel